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Chapter 26

SINGLE-PHASE INDUCTION GENERATORS

26.1 INTRODUCTION

Small portable single-phase generators are built for up to 10-20 kW.

Traditionally they use a synchronous single-phase generator with rotating diodes.

Self excited, self-regulated single-phase induction generators (IGs) provide, in principle, good voltage regulation, more power output/weight and a more sinusoidal output voltage.

In some applications, where tight voltage control is required, power electronics may be introduced to vary the capacitors “seen” by the IM. Among the many possible configurations [1,2] we investigate here only one, which holds a high degree of generality in its analysis and seems very practical in the same time. (Figure 26.1)

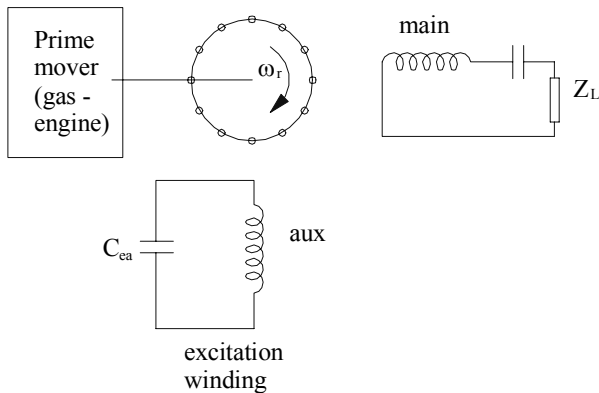


Figure 26.1 Self-excited self-regulated single-phase induction generator

The auxiliary winding is connected over a self-excitation capacitor C_{ea} and constitutes the excitation winding.

The main winding has a series connected capacitor C_{sm} for voltage self-regulation and delivers output power to a given load.

With the power (main) winding open the IG is rotated to the desired speed. Through self-excitation (in presence of magnetic saturation) it produces a certain no load voltage. To adjust the no load voltage the self-excitation capacitor may be changed accordingly, for a given IG.

After that, the load is connected and main winding delivers power to the load.

The load voltage / current curve depends on the load impedance and its power factor, speed, IG parameters and the two capacitors C_{ea} and C_{sm} . Varying C_{sm} the voltage regulation may be reduced to desired values.

In general increasing C_{sm} tends to increase the voltage at rated load, with a maximum voltage in between. This peak voltage for intermediate load may be limited by a parallel saturable reactor.

To investigate the steady state performance of single-phase IGs the revolving theory seems to be appropriated. Saturation has to be considered as no self-excitation occurs without it. On the other hand, to study the transients, the d-q model, with saturation included, as shown in Chapter 25, may be used.

Let us deal with steady state performance first.

26.2 STEADY STATE MODEL AND PERFORMANCE

Examining carefully the configuration on [Figure 25.1](#) we notice that:

- The self-excitation capacitor may be lumped in series with the auxiliary winding whose voltage is then $V_a = 0$.
- The series (regulation) capacitor C_{sm} may be lumped into the load

$$\underline{Z}'_L = \underline{Z}_L - \frac{jX_C}{F} \quad (26.1)$$

F is the P.U. frequency with respect to rated frequency. In general

$$\underline{Z}_L = R_L + jX_L \cdot F \quad (26.2)$$

Now with $V_a = 0$, the forward and backward voltage components, reduced to the main winding, are ($V_a = 0$, $V_m = V_s$)

$$V_{m+} = V_{m-} \quad (26.3)$$

$$V_{m+} = V_s/2 = -Z_L(I_{m+} + I_{m-})/2 \quad (26.4)$$

Equation (26.4) may be written as

$$\begin{aligned} \underline{V}_{AB} = V_{m+} &= -\frac{\underline{Z}'_L}{2}(I_{m+} + I_{m-}) = -\underline{Z}'_L I_{m+} + \frac{\underline{Z}'_L}{2}(I_{m+} - I_{m-}) \\ \underline{V}_{AB} = V_{m-} &= -\frac{\underline{Z}'_L}{2}(I_{m+} + I_{m-}) = -\underline{Z}'_L I_{m-} - \frac{\underline{Z}'_L}{2}(I_{m+} + I_{m-}) \end{aligned} \quad (26.5)$$

Consequently, it is possible to use the equivalent circuit in [Figure 24.5](#) with $\underline{Z}'_L$ in place of both $\underline{V}_{m+}$ (V_{AB}) and $\underline{V}_{m-}$ (V_{BC}) as shown in [Figure 26.2](#). Notice that $-\underline{Z}'_L/2$ also enters the picture, flowed by $(I_{m+} - I_{m-})$, as suggested by Equations (26.5).

All parameters in [Figure 26.2](#) have been divided by the P.U. frequency F . Denoting

$$\begin{aligned}
\underline{Z}_{1mL} &= \frac{R_{sm}}{F} + jX_{sm} + \frac{R_L}{F} + jX_L - j\frac{X_{csm}}{F^2} \\
\underline{Z}'_{aL} &= \frac{R_{sa}}{2Fa^2} + j\frac{X_{sa}}{2a^2} - j\frac{X_{cea}}{2F^2a^2} - \frac{\underline{Z}_{1mL}}{2} \\
\underline{Z}_+ &= \frac{jX_{mm}\left(\frac{R_{rm}}{F-U} + jX_{rm}\right)}{\frac{R_{rm}}{F-U} + j(X_{mm} + X_{rm})} \\
\underline{Z}_- &= \frac{jX_{mm}\left(\frac{R_{rm}}{F+U} + jX_{rm}\right)}{\frac{R_{rm}}{F+U} + j(X_{mm} + X_{rm})}
\end{aligned} \tag{26.6}$$

the equivalent circuit of Figure 26.2 may be simplified as in Figure 26.3.

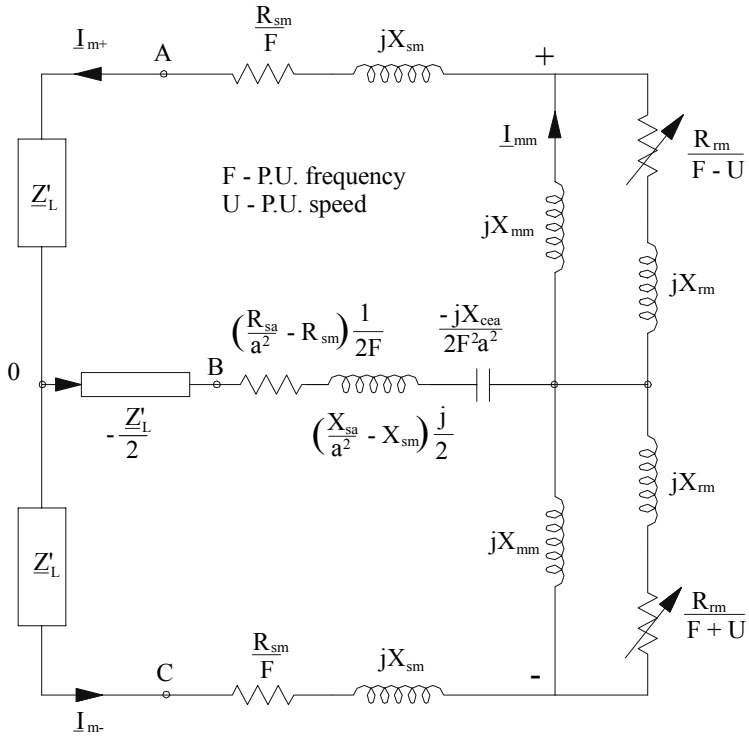


Figure 26.2 Self-excited self-regulated single-phase IG (Figure 26.1): equivalent circuit for steady state

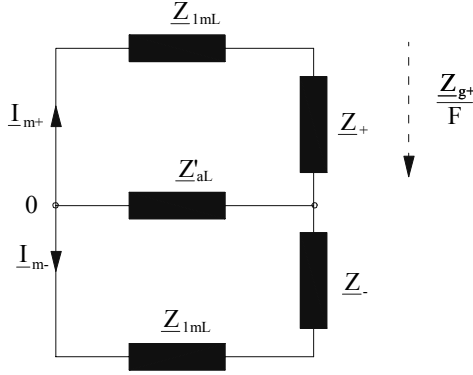


Figure 26.3 Simplified equivalent circuit of single-phase generator

The self-excitation condition implies that the sum of the currents in node 0 is zero:

$$\frac{1}{\underline{Z}_{1mL} + \underline{Z}_+} = \frac{1}{\underline{Z}_{1mL} + \underline{Z}_-} + \frac{1}{\underline{Z}'_{aL}} \quad (26.7)$$

Two conditions are provided by (26.7) to solve for two unknowns. We may choose F and X_{mm} , provided the magnetisation curve: $V_{g+}(X_{mm})$ is known from the measurements or from FEM calculations.

In reality, X_{mm} is a known function of the magnetisation current: I_{mm} : $X_{mm}(I_{mm})$ (Figure 26.4).

To simplify the computation process we may consider that $\underline{Z}_-$ is

$$\underline{Z}_- \approx \frac{R_{rm}}{F + U} + jX_{rm} \quad (26.8)$$

Except for X_{mm} , as all other parameters are considered constant, we may express $\underline{Z}_+$ from (26.7) as:

$$\underline{Z}_+ = \frac{(\underline{Z}_{1mL} + \underline{Z}_-) \cdot \underline{Z}'_{aL}}{\underline{Z}_{1mL} + \underline{Z}_- + \underline{Z}'_{aL}} - \underline{Z}_{1mL} \quad (26.9)$$

All impedances on the right side of Equations (26.9) are solely dependent on frequency F , if all motor parameters, speed n and C_{ae} , C_{sm} , X_L are given, for an adopted rated frequency f_{In} .

For a row of values for F we may simply calculate from (26.9) $\underline{Z}_+ = f(F)$ for given speed n , capacitors, load

$$\underline{Z}_+(F, X_{mm}) = \frac{jX_{mm} \left(\frac{R_{rm}}{F - U} + jX_{rm} \right)}{j(X_{mm} + X_{rm}) + \frac{R_{rm}}{F - U}} \quad (26.10)$$

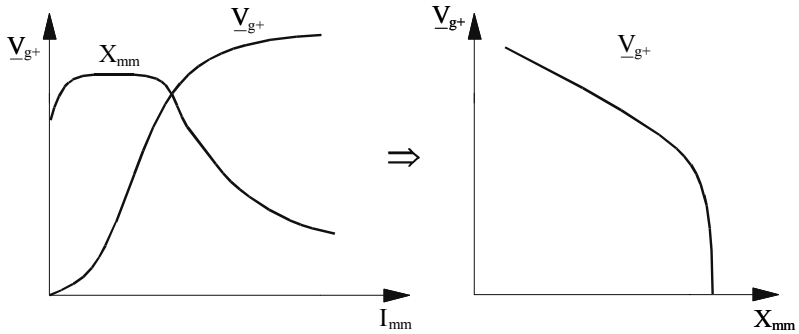


Figure 26.4 The magnetization curves of the main winding

We may use only the imaginary part of (26.10) and determine rather simply the $X_{mm}(F)$ function.

Now, from Figure (26.4), we may determine for each F , that is for every X_{mm} value, the airgap voltage value V_{g+} and thus the magnetization current

$$I_{mm} = \frac{V_{g+}}{X_{mm}} \quad (26.11)$$

As we now know F , X_{mm} and V_{g+} , the equivalent circuit of Figure 26.3 may be solved rather simply to determine the two currents I_{m+} and I_{m-} .

From now on, all steady state characteristics may be easily calculated.

$$I_{m+}^{(F)} = \frac{V_{g+}}{F} \cdot \frac{1}{\left(\frac{Z_{lmL}}{Z_{al}'} + \frac{Z_{lmL}}{Z_{al}' + Z_{lmL}} \right)} \quad (26.12)$$

$$I_{m-}^{(F)} = I_{m+}^{(F)} \cdot \frac{Z_{al}'}{Z_{-} + Z_{lmL}} \quad (26.13)$$

The load current I_m is

$$I_m = I_{m+} + I_{m-} \quad (26.14)$$

The auxiliary winding current writes

$$I_a = j(I_{m+} - I_{m-}) \quad (26.15)$$

The output active power P_{out} is

$$P_{out} = I_m^2 \cdot R_L \quad (26.16)$$

The rotor + current component I_{r+} becomes

$$I_{r+} = -I_{m+} \cdot \frac{jX_{mm}}{\frac{R_{rm}}{F - U} + j(X_{rm} + X_{mm})} \quad (26.17)$$

The total input active power from the shaft P_{input} is

$$P_{input} \approx 2I_{r+}^2 \cdot \frac{R_{rm} \cdot U}{F - U} - 2I_{m-}^2 \cdot \frac{R_{rm} U}{F + U} \quad (26.18)$$

For a realistic efficiency formula, the core additional and mechanical losses $p_{iron} + p_{stray} + p_{mec}$ have to be added to the ideal input of (26.18).

$$\eta = \frac{P_{out}}{P_{input} + p_{iron} + p_{stray} + p_{mec}} \quad (26.19)$$

As the speed is given, varying F we change the slip. We might change the load resistance with frequency (slip) to yield realistic results from the beginning.

As $X_{mm}(V_{g+})$ may be given as a table, the values of $X_{mm}(F)$ function may be looked up simply into another table. If no X_{mm} is found from the given data it means that either the load impedance or the capacitors, for that particular frequency and speed, are not within the existence domain.

So either the load is modified or the capacitor is changed to reenter the existence domain.

The above algorithm may be synthesized as in [Figure 26.5](#).

The IG data obtained through tests are: $P_n = 700$ W, $n_n = 3000$ rpm, $V_{Ln} = 230$ V, $f_{1n} = 50$ Hz, $R_{sm} = 3.94$ Ω , $R_{sa} = 4.39$ Ω , $R_{rm} = 3.36$ Ω , $X_{rm} = X_{sm} = 5.48$ Ω , $X_{sa} = 7.5$ Ω , unsaturated $X_{mm} = 70$ Ω , $C_{ea} = 40$ μ F, $C_{sm} = 100$ μ F [1].

The magnetization curves $V_{g+}(I_m)$ has been obtained experimentally, in the synchronous bare rotor test. That is, before the rotor cage was located in the rotor slots, the IG was driven at synchronism, $n = 3000$ rpm ($f = 50$ Hz), and was a.c.-fed from a Variac in the main winding only. Alternatively it may be calculated at standstill with d.c. excitation via FEM. In both cases the auxiliary winding is kept open. More on testing of single-phase IMs in Chapter 28. The experimental results in [Figure 26.6](#) warrant a few remarks

- The larger the speed, the larger the load voltage
- The lower the speed, the larger the current for given load
- Voltage regulation is very satisfactory: from 245 V at no load to 230 V at full load
- The no load voltage increases with C_{ea} (the capacitance) in the auxiliary winding
- The higher the series capacitor (above $C_{sm} = 40$ μ F) the larger the load voltage
- It was also shown that the voltage waveform is rather sinusoidal up to rated load
- The fundamental frequency at full load and 3,000 rpm is $f_{1n} = 48.4$ Hz, an indication of small slip

A real gas engine (without speed regulation) would lose some speed when the generator is loaded. Still the speed (and additional frequency) reduction from no load to full load is small. So aggregated voltage regulation is, in these conditions, at full load, slightly larger but still below 8% with a speed drop from 3000rpm to 2920rpm [1].

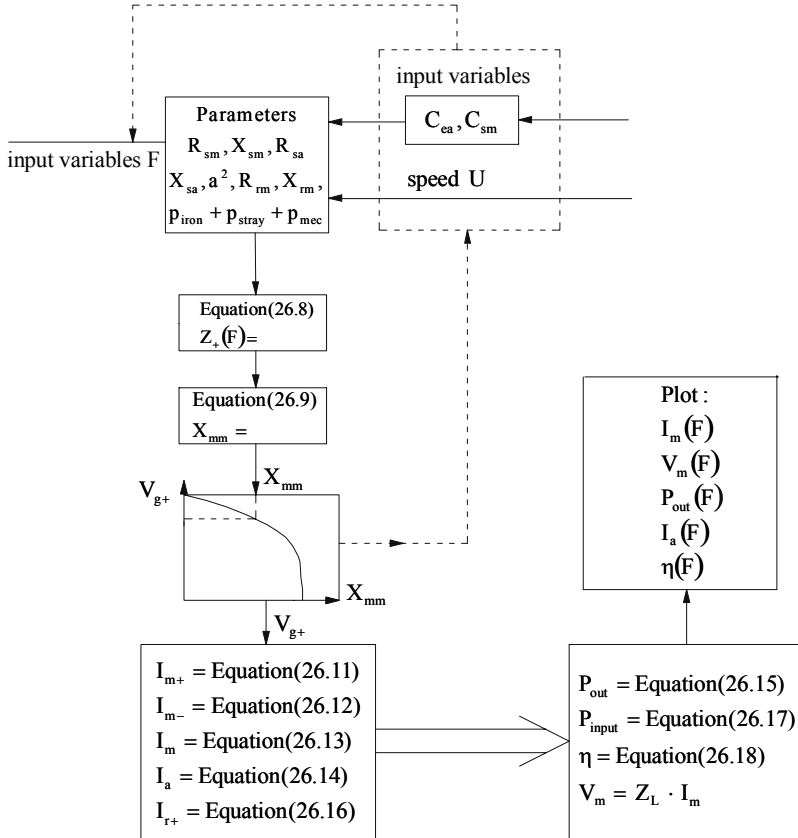


Figure 26.5 Performance computation algorithm

Typical steady state performance obtained for such a self-regulated single-phase IG are shown in [Figure 26.6](#). [1]

26.3 THE d-q MODEL FOR TRANSIENTS

The transients may be treated directly via d-q model in stator coordinates with saturation included (as done for motoring).

$$V_{ds} = -V_{csm} - R_L I_{ds} - L_L \frac{dI_{ds}}{dt} \quad (26.20)$$

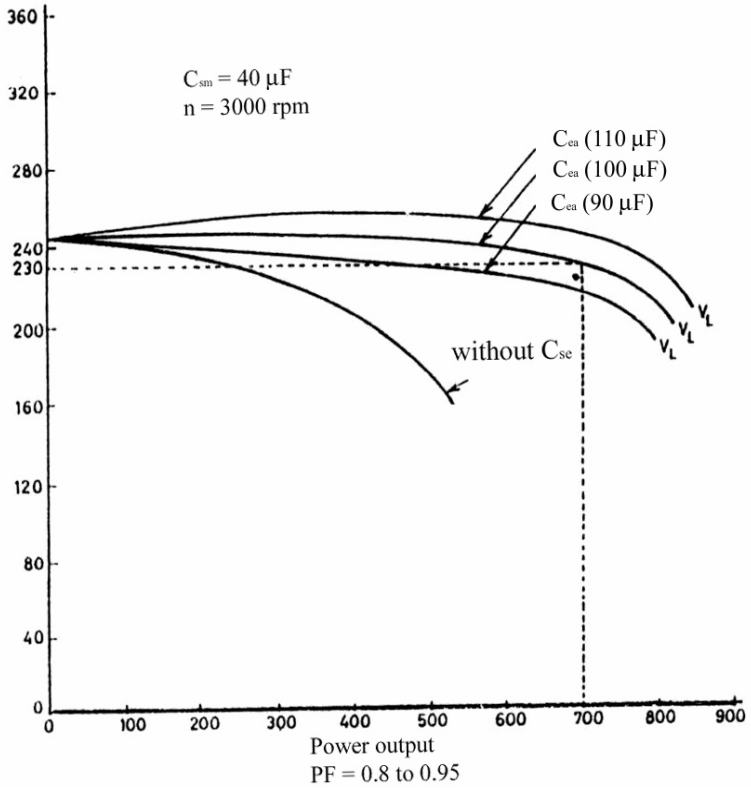


Figure 26.6 Steady state performance of a self-excited self-regulated single-phase IG

$$\frac{dV_{csm}}{dt} = \frac{1}{C_{sm}} I_{ds}; I_{ds} = I_m \quad (26.21)$$

$$V_q = -V_{cea} \quad (26.22)$$

$$\frac{dV_{cea}}{dt} = \frac{1}{a^2 C_{ea}} I_{qs}; I_{qs} = I_a \cdot a \quad (26.23)$$

The d-q model in paragraph (25.2) is:

$$\begin{aligned}
\frac{d\Psi_{ds}}{dt} &= V_{ds}(t) - R_{sm} I_{ds} \\
\frac{d\Psi_{qs}}{dt} &= -V_{cea} - \frac{R_{sa}}{a^2} I_{qs} \\
\frac{d\Psi_{dr}}{dt} &= I_{dr} R_{rm} - \omega_r \Psi_{qr} \\
\frac{d\Psi_{qr}}{dt} &= I_{qr} R_{rm} - \omega_r \Psi_{dr}
\end{aligned} \tag{26.24}$$

$$\begin{aligned}
\Psi_{ds} &= L_{sm} I_{ds} + \Psi_{dm}; \Psi_{dm} = L_{mm} I_{dm} \\
\Psi_{dr} &= L_{rm} I_{dr} + \Psi_{qm}; \Psi_{qm} = L_{mm} I_{qm} \\
\Psi_{qs} &= \frac{L_{sa}}{a^2} I_{qs} + \Psi_{qm}; I_{dm} = I_{ds} + I_{dr} \\
\Psi_{qr} &= L_{rm} I_{qr} + \Psi_{qm}; I_{qm} = I_{qs} + I_{qr} \\
\text{and } \Psi_m &= L_{mm} (I_m); I_m; I_m = \sqrt{I_{dm}^2 + I_{qm}^2}
\end{aligned} \tag{26.25}$$

To complete the model the motion equation is added

$$\begin{aligned}
\frac{J}{p_l} \frac{d\omega_r}{dt} &= T_{pmover} + T_e \\
T_e &= p_l (\Psi_{ds} I_{qs} - \Psi_{qs} I_{ds}) < 0
\end{aligned} \tag{26.26}$$

The prime mover torque may be dependent on speed or on the rotor position also. The prime mover speed governor (if any) equations may be added.

Equation (26.20) shows that when the load contains an inductance L_L (for example a single-phase IM), I_{ds} has to be a variable and thus the whole d-q model (Equation 26.24) has to be rearranged to accommodate this situation in presence of magnetic saturation.

However, with resistive load (R_L) - $L_L = 0$ -the solution is straightforward with: V_{csm} , V_{cea} , Ψ_{ds} , Ψ_{qs} , V_{qs} , Ψ_{dr} , Ψ_{qr} and ω_r as variables.

If the speed ω_r is a given function of time the motion equation (26.26) is simply ignored. The self-excitation under no load, during prime mover start-up, load sudden variations, load dumping, or sudden shortcircuit are typical transients to be handled via the d-q model.

26.4 EXPANDING THE OPERATION RANGE WITH POWER ELECTRONICS

Power electronics can provide more freedom to the operation of single-phase IMs in terms of load voltage and frequency control. [3] An example is shown on [Figure 26.7](#) [4].

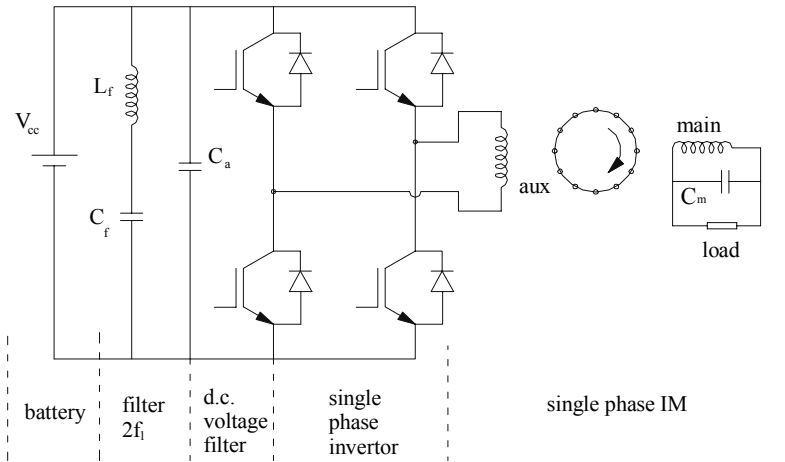


Figure 26.7 Single-phase IG with battery-inverter-fed auxiliary winding

The auxiliary winding is now a.c. fed at the load frequency f_1 , through a single-phase inverter, from a battery.

To filter out the double frequency current produced by the converter, the $L_f C_f$ filter is used. C_a filters the d.c. voltage of the battery.

The main winding reactive power requirement may be reduced by the parallel capacitor C_m with or without a short or a long shunt series capacitor.

By adequate control in the inverter, it is possible to regulate the load frequency and voltage when the prime mover speed varies.

The inverter may provide more or less reactive power.

It is also possible that, when the load is large, the active power is contributed by the battery. On the other hand, when the load is low, the auxiliary winding can pump back active power to recharge the battery.

This potential infusion of active power from the battery to load may lead to the idea that, in principle, it is possible to operate as a generator even if the speed of the rotor ω_r is not greater than $\omega_1 = 2\pi f_1$. However, as expected, more efficient operation occurs when $\omega_r > \omega_1$.

The auxiliary winding is 90° (electrical) ahead of the main winding and thus no pulsation type interaction with the main winding exists. The interaction through the motion e.m.f.s is severely filtered for harmonics by the rotor currents. So the load voltage is practically sinusoidal. The investigation of this system may be performed through the d-q model, as presented in the previous paragraph.

For details, see Reference 4.

26.5 SUMMARY

- The two winding induction machine may be used for low power autonomous single-phase generators.

- Amongst many possible connections it seems that one of the best connects the auxiliary winding upon an excitation capacitors C_{ea} , while the main winding (provided with a self-regulation series capacitors C_{sm}) supplies the load.
- The steady state modelling may be done with the revolving theory (+,-or f, b) model.
- The saturation plays a key role in this self-excited self-regulated configuration
- The magnetic saturation is related, in the model, to the direct (+)-forward-component.
- A rather simple computer program can provide the steady state characteristics: output voltage, current, frequency versus output power for given speed, machine parameters and magnetization curve.
- Good voltage regulation (less than 8%) has been reported.
- The sudden shortcircuit apparently does not threaten the IG integrity.
- The transients may be handled through the d-q model in stator coordinated via some additional terminal voltage relationships.
- More freedom in the operation of single-phase IG is brought by the use of a fractional rating battery-fed inverter to supply the auxiliary winding. Voltage and frequency control may be provided this way. Also, bi-direction power flow between inverter and battery can be performed. So the battery may be recharged when the IG load is low.
- In the power range (10-20kW) the single-phase IG represents a strong potential competitor to existing gensets using synchronous generators.

26.6 REFERENCES

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4. O. Ojo, O. Omozusi, A. A. Jimoh, Expanding the Operating Range of a Single-Phase Induction Generator with a PWM Inverter, Record of IEEE-IAS-1998, vol. 1, pp. 205-212.